LANL Workshop on

Closing the Gap between Infrastructure Assessments and Climate Simulation

Workshop Goals

> ***This workshop aims to develop a compelling technical focus for needs at the interface between infrastructure assessment/adaptation and climate simulation.***

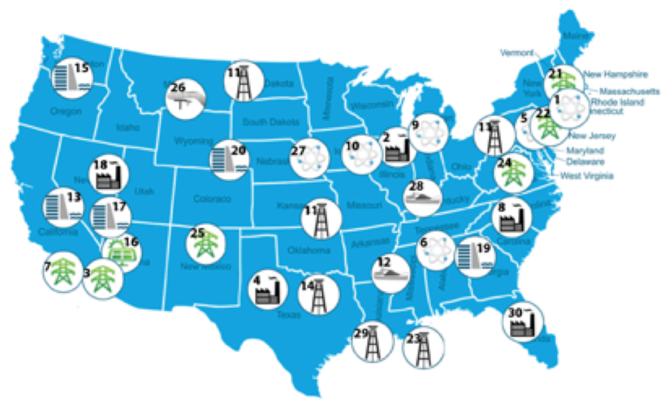
LANL has active but distinct research portfolios in simulation of both climate scenarios and infrastructures. Both communities have recognized the opportunity for a closer coordination, for example, by using climate simulations to bound future scenarios needed for infrastructure assessments. It is a goal voiced by the broader research community and by many sponsors, yet it remains elusive.

As part of a capability development effort by ADCLES, ADTIR, and ADTSC, this workshop will bring together the LANL research community to explore technical challenges and potential opportunities in bridging the gap between climate simulations and energy-infrastructures assessments, including vulnerabilities and adaptation. The output of this workshop will be used to develop the technical focus in a LANL strategy for capability enhancement, partner identification, and program development.

Climate Impacts to Infrastructure

> ***Weather impacts to infrastructure—particularly related to energy and lifeline—are central to public and private planning, for both near-term (e.g., preparing for event response) and long-term (e.g., in planning for infrastructure investments for resilience, adaptation, & efficiency).***

Maintaining efficient energy and lifeline infrastructures is central to the mission of DOE as well as to the missions of other federal and state agencies. This mission falls into two categories: resilience to short time scale, episodic events (e.g., hurricanes; heat waves) and planning for long-term infrastructure investments.



Selected events over the last decade illustrate the U.S. energy sector's vulnerabilities to clime (DOE, 2013).

These two categories are linked via the dependence of short-term episodic events on the nature of long term climate change Both resilience to episodic events and cost effective investments over the long term are recognized as as being critical to the U.S. energy strategy. Given both the aging state of the existing infrastructure and the importance of the infrastructure (particularly the grid) in enabling a robust energy portfolio, now is an opportune time to reconsider a new approach to the use of climate predictions to inform infrastructure planning and assessment.

DOE (2013) recognized three categories of phenomena that have posed historical vulnerabilities to the U.S. energy sector due to climate change and extreme weather:

- increasing temperatures (including air and water temperatures and impacts on permafrost, evaporation, snow, and ice),
- change in water availability, and
- change in storms/flooding/sea-level.

These phenomena impact all aspects of the energy infrastructure, including fuel production, transportation, energy production/conversion, and transmission (Schaeffer et al., 2012).

The effects of climate change on infrastructure are not unique to the continental US. DOE (2013) notes the Arctic is particularly vulnerable to climate change with temperature changes twice as fast as global averages (IPCC, 2007). Given the vast resources in the Arctic—USGS estimates 30% of the global undiscovered gas and 13% of the undiscovered oil (Gautier, 2009)—these vulnerabilities have important implications for future energy-related costs; Larsen et al. (2008) estimated $3–6B through 2030 for impacts to Alaska's public infrastructure. DoD (2014) notes the importance of these impacts beyond the U.S. borders, which are anticipated to increase the need for disaster relief and humanitarian assistance overseas and air/sea/land support in the Arctic while increasing instability within/among other nations.

Current Approach to Climate & Infrastructure

Current approaches to infrasture assessment and planning rely on empirical weather data derived from historical trends, including geospatial distributions of both mean values and extreme values. Planning typically does not consider climate-driven changes in demand for services from infrastructure, nor does it consider possible correlations in regional availability of resources needed to serve these demands.

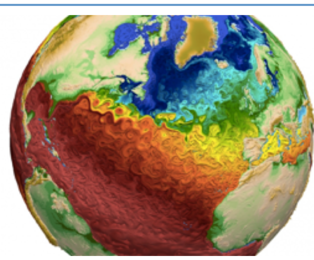
Several direct climate/weather factors are relevant to infrastructure assessments: temperature, precipitation, and storm frequency, among others. In addition, these factors have indirect impacts on infrastructure through phenomena such as surface water processes, sea level and forest fires, which in turn have important feedbacks on regional weather patterns, population distribution, and resource availability.

Current approaches to characterizing weather-related impacts on infrastructure rely on empirical data derived from historical trends. However, climate change challenges the use of historical data to predict future trends, leading to a grand challenge for predictions of the natural system as needed to assess potential impacts to the energy infrastructure:

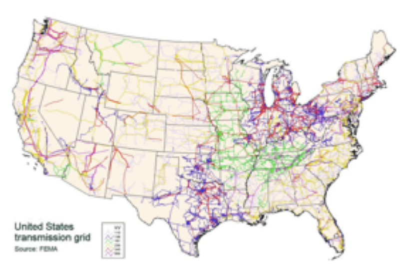
- *Improving climate-related risk assessments of infrastructure through the use of probabilistic methods to couple high fidelity climate predictions at the national- and regional-scales.* From an infrastructure perspective, these risk assessments must be based on modeling and optimization at times scales relevant to service lifetime of infrastructure investments (e.g., decades to centuries) and must address socio-economic factors and future resource availability. From a climate perspective, new probabilistic methods are needed to account for spatiotemporal correlations in the climate/weather that could exacerbate infrastructure impacts and/or could be exploited as part of an adaptation strategy.

The Gap between Climate and Infrastructure

Climate predictions could be used to inform assessment of infrastructure impacts, but the outputs from such predictions are not currently ammenable to serve as inputs into impact assessments.



Simulated ocean temperatures illustrate level of detail achievable in current climate simulations. DOE-SC investments are targeting 10-km resolution, which could enable regional-scale climate assessments.



Map of U.S. transmission grid (FEMA) illustrates national-level complexity in one of many interconnected infrastructures that must be simulated to assess vulnerabilities. Regional-scale complexity is even higher.

Anthropogenic climate change is likely to alter global weather patterns in complex ways that cannot be simply extrapolated from historical trends, introducing uncertainties and correlations that impact both near- and long-term planning. These climate-related impacts range from changes in distributions of temperature, water availability, and sea level to changes in the frequency, duration, and severity of extreme weather events.

Advances in climate prediction offer the potential to enable a strategic regional and national approach to planning and preparedness for energy infrastructure: predictive models are achieving a level of completeness and complexity that begins to capture climate evolution at regional scale in response to the complex coupling between atmosphere, ocean, land-mass, ecology, etc. DOE-SC's recent goal is to achieve resolutions of 10 km in climate models, which can resolve atmospheric processes that control the distribution and magnitude of extreme events and mesoscale eddies that carry much of the energy in the ocean. This goal has become achievable due to recent DOE investments in high performance computing.

Advances in interdependent infrastructure simulation—including probabilistic risk assessment and multi-infrastructure designoptimization—offer the potential to utilize climate modeling and simulation outputs to create a multi-scale, risk-aware, time-extended simulation and optimization environment for both exploring and directing infrastructure adaptation models. Integration and automation of interdependent infrastructure and natural systems simulation enables the rapid exploration of the resilience and probabilistic risk assessment of local-scale infrastructure to a wide rant of complex threats ranging sea level rise, hurricanes, extreme rainfall, inland flooding, and severe ice storms. Advancements in optimization techniques such as new relaxations and heuristic methods are making optimal designs of large-scale interdependent infrastructure networks computationally tractable.

Bringing these two components together can lead to a level of accuracy in understanding potential climate–infrastructure impacts that is needed for effective planning in the context of infrastructure investments and resilince to extreme events.

However, to achieve this integration of climate predictions and infrastructure assessment and design requires addressing several challenges:

- *Outputs from climate predictions are not directly usable in risk assessments of infrastructure impacts*. Models do not currently predict all of the relevant interface variables that drive infrastructure design. For those that are predicted, they are often not available on useful time scales or expressed in an appropriate structure, e.g. predictions of seasonal mean regional temperature versus predictions of distributions or extreme of daily temperatures.
- *Integrated formulations of large-scale infrastructure optimization and simulation models do not yet account for the wide disparities of spatial and temporal scales needed to simultaneously represent both local resilience to extreme episodic events and regional-scale adaption and economic efficiency over long time scales.*
- *Stakeholders (particularly federal stakeholders) cross many organizations, resulting in no focused federal program.*

The first two of these impediments are technical and represent an opportunity for LANL and DOE. They reflect the need for identifying the appropriate spatiotemporal resolution for both climate simulations and infrastructure assessment such that the two can be coupled while capturing the necessary detail (including interdependencies and correlations). For example, DOE Office of Science is developing higher resolution, but slower runninng, models of future climate. These are the best models available for simulating climate, but may not be suitable for capturing the correlations between large-scale climate variables, quantifying the uncertainty over impacts or in developing optimal responses to that uncertainty. For these tasks, fast climate emulation may prove more useful. Similary, high spatial resolution models of infrastructure (e.g. down to the wires and pipes) may be far too computationally challenging for assessing impacts and developing adaption strategies on a national scale. Instead, for fine-scale local infrastructure like electrical distribution or local water systems, something akin to "infrastructure emulation" that captures the change in gross infrastructure qualities (e.g. resilience or efficiency) driven by changes in gross inputs (e.g. dollars invested) may prove far more useful. These models may be especially useful when coupled to climate models that reveal large-scale correlations in climate behavior.

A Strawman Technical Approach to Closing the Gap

> ***The workshop organizers believe a link can be established between climate simulation and infrastructure using core LANL capabilities in integrating simulation and uncertainty quantification for prediction, using exascale simulation to build probabilistic data models that describe the predicted behavior of climate over time at the regional scale, and multiscale simulation and optimization of infrastructure adaptation to evolving climate risk.***

Numerical simulations are the most reliable way to produce credible process-based projections of the future climate. However, even state-of-the-art simulations inevitably contain biases and are so computationally expensive as to hinder comprehensive uncertainty analysis. These limit the direct usefulness of Earth system models for infrastructure vulnerability and adaptation assessments. One path forward is a fast "emulation" approach that combines observational data and multi-fidelity simulation output to link climate variability and extreme weather dynamics, providing probabilistic risk information to infrastructure simulations (Kopp et al. 2014; van Maanen et al. 2015). This new "risk projection model" would represent a convergence between numerical-physical Earth system modeling and the statistical-empirical catastrophe risk ("cat-risk") modeling more common to the insurance industry (Grossi & Kunreuther, 2005).

The same limitations also exist in integrated assessment models of coupled natural-human-engineered systems. In particular, adapatation dynamics at the level of individual infrastructure assets is embedded in a larger system of national infrastructure and resource availability; at the same time, infrastructure hardening and siting decisions feed back to this larger scale. There are close links between infrastructure and the natural Earth system, such as ecosystems buffering population centers from storms, and urban development disturbing ecosystems and land surface processes. The result is a high-complexity, multiscale, nonlinear system with threshold behavior as failures cascade through interdependent systems. This already-complex system may become further embedded within nested multiscale optimization loops when human decision making is represented. This calls for emulation of not only infrastructure dynamics at multiple scales, but of adaptation policies and their feedbacks to other system components. Policies should be robust with respect to both present-day uncertainty and the possibility of new information arriving over time (Powell 2011; Powell and Ryzhov 2012).

There are potential links to information science and technology beyond emulation, uncertainty quantification, and optimization. For example, one approach to high-fidelity Earth system modeling advocates a "seamless prediction" program, where a numerical model is expected to be useful both in a short-term weather prediction and long-term climate projection setting (Palmer et al., 2008; Hurrell et al., 2009). The same approach could be taken an operational forecasting (http://espc.oar.noaa.gov/) or a probabilistic risk projection setting. For example, a cat-risk type model that forecasts the exposure of infrastructure assets to hurricane intensification based on climate projections could also be expected to perform well as an operational hurricane statistical forecast model. This would lend credibility and historical validity to its longer-term projections. Machine learning techniques could be used to identify new nonlinear features/signatures useful for prediction, or even to provide statistical models that can be used in place of numerical models for highly efficient data assimilation and forecasting of both climate and weather and infrastructure response. These same methods could be applied to foreign infrastructure networks in an access-denial setting to evaluate their vulnerability to natural and non-natural threats.

Climate infrastructure adaptation has a range of potential customers with different interests. DOE-SC is interested in regional interdependencies and feedbacks to the larger economic and Earth systems. DOE-OE is interested in economic efficient and reliability of energy infrastructures. DHS and regional/local stakeholders are interested in resilience of individual cities and regional critical infrastructures. DOD is interested in the vulnerability of military assets as well as global security concerns (the IC community as well). A technical approach to this problem should be designed to satisfy multiple customers, useful for both federal planning and local decision making. Indeed, utility in local decision making can inform higher-level representations of climate adaptation strategies ("upscaling"), and high-level socioeconomic, regulatory, and technological-change dynamics can inform the constraints that local decision makers can expect to operate under in the future.

Background Reading

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